

# The Soil Microbial Community and Soil Tillage

Diva Souza Andrade, Arnaldo Colozzi-Filho, and Ken E. Giller

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## 3.1 INTRODUCTION

As a consequence of intense cultivation under the traditional practices of plowing and disking to prepare land, much of the original surface soil fertility of most agricultural soils is lost, either through erosion or organic depletion.<sup>29</sup> Concerns about soil productivity include biological soil quality as well as an increasing interest in management of soil organic matter,<sup>31</sup> which is related to the activity of many

different types of microorganisms. Therefore, alternative techniques of cropping cultivations and soil management defined as conservation agriculture that include no-tillage (NT) or conservation tillage are being widely adopted throughout many parts of world. This practice has been adopted in most South and North American countries and other continents as an agronomic system of soil management that aims either to allow the recovery soils from degradation or to prevent soil erosion. For instance, in the south of Brazil, in the early 1970s, several soil tillage field experiments were carried out,<sup>46,140,158</sup> and since then, based on their best performance, farmers have gradually replaced conventional tillage (CT) with NT, which is also called zero tillage.

Farmers have adopted these minimum tillage systems and crop rotations seeking soil productivity and sustainability, so studies considering the effects of these systems on soil microbial biomass and its activity in the soil are essential.<sup>102</sup> Regarding the short- and long-term effects of intense soil cultivation, especially plowing, on microbial communities, there are many studies on microbial biomass. Specific groups of microorganisms which are important to agricultural activity, such as rhizobia and mycorrhizal fungi, have been the subjects of both short- and long-term experiments aimed at evaluating soil tillage effects. Few studies based on molecular biology techniques have examined relationships between the diversity of the microbial community, or on specific groups of microorganisms, and soil tillage.

The purpose of this chapter is to analyze published results and to explore the implications of tillage on microbial communities, with particular reference to specific microbial groups such as mycorrhizal fungi, rhizobia, and ammonifying and nitrifying bacteria. These microorganisms are of great importance in agriculture because they are involved in biochemical processes that include cycles of essential nutrients such as N and P. Eventually, two questions arise: first, what effects does soil tillage have on the microbial communities? It has been suggested that agriculture creates a highly selective and homogenous environment, which reduces microbial activity and diversity. Conversely, it has been argued that cultivation results in more diverse microbial community due to improvements in soil conditions. Second, what are the means of conserving the contributions of soil microorganisms to crop productivity? The objective of this review is to examine means of guaranteeing conservation of biodiversity and elucidating relationships between soil tillage and microbial activity.

## **3.2 SOIL MICROBIAL COMMUNITY AS A COMPONENT OF AGROECOSYSTEMS**

The soil microbial population is composed of protozoa, algae, fungi, actinomycetes, bacteria, and viruses, and these components contribute to the sustenance and productivity of agroecosystems as well as sometimes act as diseases that can reduce plant productivity.<sup>74</sup> The size of these populations and the activity of each of these groups of microorganisms have wide ranges that are influenced by both biotic and abiotic factors.

Agroecosystems can be defined as land-use systems that produce food and fiber, a process that is governed by many factors and components such as soil type,

cropping patterns, and tillage management. The importance of microorganisms in the agroecosystems depends on the functional groups present, which are active participants in the various vital processes for plant nutrition. Although most agricultural land uses affect various beneficial microorganisms, some practices seem to be less harmful than others. Even though we still know little about the best management for soil quality or healthy soils, we believe that fewer cultivations are generally beneficial to the microbial community. A number of reviews of tillage effects on soil organic matter in temperate regions<sup>127</sup> and on soil biochemical and microbial relationships are available.<sup>48,60</sup>

The NT system is characterized by sowing of crops directly into the crop residues that remain from the previous crop without soil preparation measures (e.g., plowing and disking), except for a narrow slit required for seed placement.<sup>146</sup> The crop residues are left on the soil surface as mulch, acting as a barrier against soil. In NT systems, residue decomposition is slow due to the partial contact between crop residues and soil, which results in higher organic matter content in comparison with CT. Consequently, there is an increase in organic C and total N and the more labile organic material, including the microbial biomass,<sup>32,86</sup> in the soil under NT than in CT system.

In NT systems, cover- and crop-rotation practices improve the chances towards the sustainable agriculture. The proportion of organic material added to the soil remaining after decomposition is the main factor controlling organic matter contents in soil ecosystems.<sup>45</sup> Alterations in the amount and in quality of the organic matter of soils by cultivation results in a great impact on soil properties, influencing nutrient release and microbial activity.<sup>101</sup> The long-term maintenance of a significant amount of organic matter on the soil surface is important because it minimizes extreme temperature shifts and maintains adequate moisture and contributes to aeration. This is likely to result in improved soil structure (see [Chapter 2](#)), fertility, and biological activity. Maintenance of water retention in the soil during hot spells and droughts is the expected outcome.<sup>46,140</sup> Due to these effects of the NT system there are wide qualitative and quantitative changes in microorganism populations and activities.<sup>51</sup> These observed benefits are attributed to the improved conditions for the many groups of microorganisms reported to be significant for key processes in soil ecosystems.

### **3.2.1 Contribution of Microbial Communities to Agroecosystem Functioning**

The microbial community represents only a small part of total soil organic matter, ranging between 1 and 8%, but it affects crop production by acting as catalysts for biotransformations.<sup>132</sup> Due to their role in soil pedogenesis and morphology, soil microorganisms are of key significance for sustainability of agroecosystems, in particular because of their effects on the soil nutrient status and soil-plant interactions. Soil microorganisms are agents and regulators in main biochemical processes such as inorganic transformations of N, P, and S, metabolite production, agrochemical degradation, and changes in the physical characteristics of the soil such as aggregation and stability of the aggregates.<sup>160</sup> In recycling organic compounds microorganisms

promote the decomposition of residues and the mineralization and absorption of nutrients by plants, contributing to crop productivity and resistance to plant diseases. Enhanced microbial activity promotes adhesion of soil particles and consequently to aggregate stability with implications for soil structure, soil moisture, and oxygen, favoring the development of plants and microorganism communities. Plants are a source of carbon in the soil, which is known to stimulate microbial activity. Nitrogen dynamics in conventional and NT agroecosystems seem to be regulated by placement of crop residues.<sup>86</sup>

There are several other functions mediated by soil microbial communities. Microorganisms can also contribute to reduction of plant stresses caused by biotic and abiotic factors<sup>144</sup> and may promote plant resistance against pathogens.<sup>124</sup> Rhizobia–legume symbioses, for example, result in biological nitrogen fixation,<sup>73</sup> whereas other symbiotic relationships are capable of improving the phosphate nutrition of plant.<sup>118</sup> Besides rhizobia  $N_2$ -fixing associations with legumes, arbuscular mycorrhizal (AM) fungi participate as another important functional group in nutrient transfer, especially phosphorus. Also, AM fungi influence water relations and pest resistance in the host plant. Microorganisms mediate several metabolic processes in the soil; therefore, it is likely that soil microbial diversity would be important in agricultural sustainability.<sup>112</sup> Maintenance of soil quality seems to be one of the most important activities of microorganisms in soil ecosystems.

### **3.2.2 Relationships between Microorganisms and Soil Cultivation**

Stimulated biological activity in topsoil layers as a result of mulching effects on the soil physicochemical properties tends to enhance the biological activities of microbial groups involved in residue decomposition. The cycling, metabolism, and availability of N to plants are affected by soil cultivation.<sup>52</sup> In the remaining straw, various groups of organisms proliferate, interact, and compete for biotic and abiotic resources. Predation, parasitism, and mutualisms describe the types of common relationships between the organisms. The knowledge of these processes is essential for understanding the proliferation of plant pathogens, the epidemiology of plant diseases, decomposition, and the mineralization and recycling of nutrients in the soil.<sup>99</sup> Wardle and Lavelle<sup>161</sup> suggested that, although microorganisms have a more appropriate enzymatic component to promote decomposition of cover mulches, interactions between microorganisms and soil fauna are critical for regulation of these biological processes. The predation of bacteria by protozoa can reduce enzymatic activity and contributes to reduction of decomposition rates. In this function, protozoa do not feed on bacteria alone but can prey on different mesofaunal groups or perform antibiosis relationships with higher plants.<sup>161</sup>

The nutritional quality of organic residues can also influence the rates of decomposition and recycling of nutrients. Microbial activities tend to be higher when N contents in the residues are greater, leading to a faster decomposition compared with plants residues with wider C:N ratios.<sup>26</sup> Decomposition occurs more slowly through the activity of specific microbial populations that are capable of breaking down material with low N concentration. In addition, several others site-specific factors, such as climatic or soil texture, pH, and fertility, regulate decomposition speed.<sup>84</sup>

By reducing soil disturbance, NT approaches a similar development of functional subsystems as these occur in undisturbed environments, closely resembling the patterns found in natural ecosystems.<sup>86</sup>

The soil adjacent to roots that has a different physical, chemical, and biological environment from the bulk soil and that is influenced by the plants is defined as rhizosphere.<sup>23</sup> This area has an intense microbial activity, mainly due to root exudates, which can selectively stimulate microbial populations.<sup>76,162</sup> An altering of quality or amounts of the substrates at the root interface is likely to exert direct effects on microbial activity. This may explain why grown plant species are capable of modifying the rhizosphere environments known to be important for ecosystem stability. For example, the occurrence and distribution of AM fungi are highly dependent on the presence of the host plant species, which, in turn, determines the occurrence and distribution of these fungi in the soil.<sup>151</sup> Other microorganisms in the rhizosphere are reported to affect plant growth. In producing growth hormones or growth regulators, bacteria can also influence the growth of plants,<sup>123</sup> by suppressing pathogens<sup>25</sup> or even competing with other antagonistic microorganisms in the rhizosphere.<sup>75</sup>

Where NT is adopted, temporary reductions in the contents of C and a deficiency of N may occur due to the increases in microbial activity of decomposition and the lack of incorporation of the straw into the soil.<sup>38,86</sup> However, in the long term, soils under NT accumulate more C and N as compared with CT-management systems.<sup>18,49</sup> The lower availability of N in the initial stages after transition to NT was suggested to be due to higher nitrate leaching and losses through denitrification assumed to be supported by either higher moisture and available energy in the organic matter<sup>14</sup> or greater N immobilization in the microbial biomass.<sup>130</sup>

### **3.3 ARE THE MICROBIAL COMMUNITY AND ITS COMPONENTS ALTERED DUE TO SOIL TILLAGE? HOW DO TILLAGE/CROP ROTATION PRACTICES ACT ON THE SOIL MICROBIAL COMMUNITY?**

Tillage can promote the release and degradation of previously protected organic matter, thereby contributing to long-term decreases in soil microbial biomass and organic matter.<sup>8</sup> Legume plant species play several roles in agroecosystems, in particular with regard to crop-rotation designs in NT scenarios. Among others, we highlight the following functions:

- a) They provide cover and protect the soil from water erosion.
- b) Legumes serve as sinks for plant nutrients that might otherwise be lost through leaching.
- c) They provide a source of supplemental N (legumes) and lead to slow release of nutrients.<sup>86</sup>

Shifts in the soil organic matter content reveal effects on soil physical properties, mainly on the proportion of macroaggregates.<sup>154</sup> The development of macropores is important in the maintenance of moisture and aeration of the soil, which are critical

for the survival of the microbial and their metabolic processes.<sup>57</sup> Thus, the survival of microorganisms is affected not only by differences due to aeration and smaller oscillations in soil moisture and temperature but also by processes of decomposition of both organic matter and pesticide residues and nutrient recycling. The NT system also alters chemical properties of the soil, increments in pH values, and concentrations of Ca, Mg, K, P, and CEC.<sup>140</sup> The monitored shifts intervene with the activity of soil microorganisms, subsequently affecting plant growth.

In NT systems, weed control is commonly preformed by herbicides. However, the effects of these chemicals on soil biota differ widely due to tolerance of the organisms to these ingredients. It is therefore rather difficult to draw general conclusions about herbicide effects on soil microbial communities. However, inhibition for some species or enhancement of others is likely to induce unstable conditions among the specific microorganisms involved in the degradation of organic residues. The effects of the herbicides on some specific microorganisms, such as rhizobia and mycorrhizas, have been reported to be of an indirect nature, since they decrease plant diversity, which is reported to be significant for the composition of both AM fungi populations<sup>81</sup> and native rhizobia.<sup>90</sup>

### 3.3.1 Microbial Biomass and Activity

Significant alterations of soil environments can occur rapidly after tillage. Independent of crop history or rotations, NT has been reported as a system that enhances microbial biomass in the top 0 to 10 cm of soil, compared with CT systems. Some examples of increases in the proportion of microbial carbon in relation to organic carbon in the soil under NT system are given in [Table 3.1](#). Studies under both temperate and tropical conditions showed higher levels of microbial biomass in soil under NT than in CT systems. Although there is no evidence that the assessed microbial biomass is comprised of beneficial microorganisms, Cattelan et al.<sup>39</sup> reported positive correlations between microbial biomass and fungi and soybean yields. Conversely, in another study on the same soil, Cattelan et al.<sup>40</sup> failed to confirm the observed correlations.

The objective of this chapter is to demonstrate impacts of CT and NT systems on soil microbial communities; thus, investigation data, including short- and long-term effects, from both temperate and tropical regions are summarized in Table 3.1. Microbial biomass C values ranging from 17 to 1225  $\mu\text{g g of soil}^{-1}$  were reported from data from several studies in many parts of world (Table 3.1/[Figure 3.1a](#)). In general, the microbial carbon was found to be higher under NT systems than under CT, independent of other agronomic practices. Responses of soil microbial biomass to tillage varied due to climate, duration of the experiment, sampling depth, cropping, and residue-management practices. To compare tillage effects across different locations we present NT:CT ratio values to avoid confounding differences due to soil moisture content, management of crops, times, depth of sampling, and climatic conditions. Values above 1 express an increase in the microbial biomass with NT systems. The recorded NT and CT ratios ranged from 0.7 to 3.3 (Table 3.1). Thus, an average index calculated as NT:CT microbial biomass ratio is used to highlight tillage effects. It is meant to point out that the average difference increased with duration of the

**Table 3.1 Effects of Soil Cultivation on Carbon Microbial Biomass and  $C_{\text{microbial}}/C_{\text{organic}}$  Ratio, for a Range of Soil and Climatic Conditions**

Location/ References	Time Yr	pH/ Texture	Soil Depth — cm —	Crop Rotation	Microbial Biomass		Ratio NT/CT	$C_{\text{microbial}}/C_{\text{organic}}$	
					<sup>a</sup> /NT — $\mu\text{C g soil}^{-1}$ —	CT		NT	CT
								— % —	
<b>Short-term</b>	<b>0–2</b>				<b>28–1225</b>	<b>17–1020</b>	<b>.8–1.7</b>	<b>1.2– 4.4</b>	<b>1.1– 4.0</b>
USA/ <sup>27</sup>	2d	6.9/loamy	0–15	L/C	28	17	1.6		
U.K./ <sup>113</sup>	1	/Clay	0–5	O/W	720	540	1.3	1.3	1.6
India/ <sup>106</sup>	1	6.7/Sandy loam	0–10	R/B	283	299	.9	3.29	3.05
Argentina/ <sup>3</sup>	1	5.4/Sandy loam	0–5	W	390	290	1.3	2.78	2.07
U.K./ <sup>113</sup>	2	/Clay	0–5	O/W	1210	710	1.7	2.0	1.4
Argentina/ <sup>6</sup>	2	5.9/Silt loam	0–20	W/S	280	230	1.2	1.4	1.09
Canada/ <sup>17</sup>	2	7.6/clay loam	0–10	B	1200	1020	1.2	2.85	2.34
Canada/ <sup>17</sup>	2	7.3/sandy loam	0–10	B	680	800	.8	3.58	4.0
Canada/ <sup>110</sup>	2	5.7/C-poor Luvisolic		W	1225	823	1.5	4.38	2.93
Canada/ <sup>110</sup>	2	7.2/C-rich Luvisolic		Can	710	714	1.0	1.16	1.17
New Zealand/ <sup>13</sup>	2	5.44/Silt loam	0–10	M/O	916	624	1.5		
<b>Medium-term</b>	<b>3–7</b>				<b>44–974</b>	<b>65–678</b>	<b>.7–2.5</b>	<b>.2–4.4</b>	<b>.2–3.0</b>
Brazil/ <sup>40</sup>	3	5.4/clay	0–8	W/S	383	201	1.9	2.18	1.14
Canada/ <sup>143</sup>	3	4.46/sandy/clay	0–7.5	B	603	443	1.4	1.25	.89
Italy/ <sup>58</sup>	3	8.3/	0–20	V/O/W	441	268	1.6	3.55	2.63
USA/ <sup>149</sup>	3	/Fine loamy	0–3.8	M	520	250	2.1		
USA/ <sup>24</sup>	3	5.5–6.2 clayey	0–20	M/W/S	288	374	.8		
Canada/ <sup>34</sup>	3–5	6.4/sandy loam	0–5	M	237	120	2.0	1.10	.61
Canada/ <sup>36</sup>	3–5	5.5/sandy loam	0–5	W/B	299	150	2.0	1.18	.67
Canada/ <sup>111</sup>	3–5		0–7.5	P/W/RC/SF	516	382	1.3	2.52	2.00
Canada/ <sup>36</sup>	3–5	5.5–6.4/sandy loam	0–5	W/B	299	150	2.0	1.15	.97
Argentina/ <sup>4</sup>	4	5.8 clay	0–15	M/S	414	294	1.4	.20	.18

(Continued)

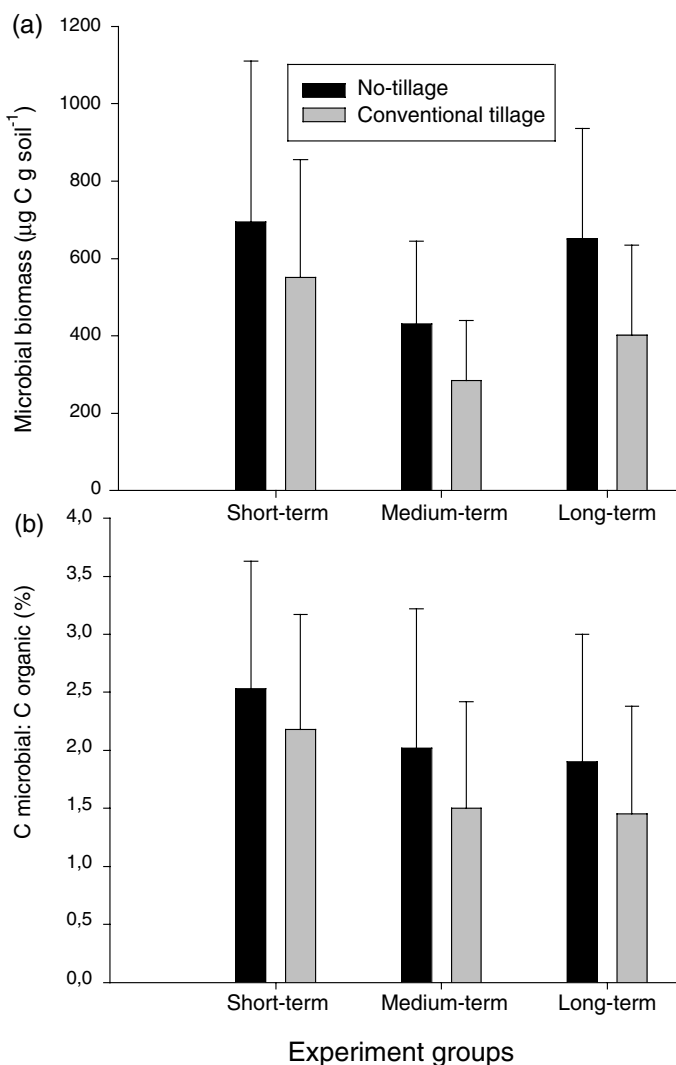
**Table 3.1 Effects of Soil Cultivation on Carbon Microbial Biomass and  $C_{\text{microbial}}/C_{\text{organic}}$  Ratio, for a Range of Soil and Climatic Conditions (Continued)**

Location/ References	Time Yr	pH/ Texture	Soil Depth — cm —	Crop Rotation	Microbial Biomass			<sup>b/</sup> $C_{\text{mic}}/C_{\text{org}}$	
					<sup>a/</sup> NT — $\mu\text{C g soil}^{-1}$ —	CT	Ratio NT/CT	NT — % —	CT
<b>Medium-term</b>	<b>3–7</b>				<b>44–974</b>	<b>65–678</b>	<b>.7–2.5</b>	<b>.2–4.4</b>	<b>.2–3.0</b>
USA/ <sup>164</sup>	4	6.1/sandy loam	0–15	*G/W	451	178	2.5	4.37	2.96
Australia/ <sup>156</sup>	5	6.1/Alfisol	0–2.5	W/leg	974	678	1.4	2.53	2.39
New Zealand/ <sup>83</sup>	5	Silt loam	0–2.5	Grass	650	400	1.6	1.75	1.25
Australia/ <sup>135</sup>	6	8/sandy	0–10	Sorghum	350	308	1.1	2.52	2.37
Canada/ <sup>134</sup>	6	coarse	0–20	M	44	65	.7		
<b>Long-term</b>	<b>8–18</b>				<b>255–1180</b>	<b>113–840</b>	<b>1.0–3.3</b>	<b>.6–3.6</b>	<b>.5–3.0</b>
Brazil/ <sup>37</sup>	8	5.3–5.1	0–10	S/M/B	469	315	1.5	.90	.25
USA/ <sup>68</sup>	9	8.2/silt loam	0–5	W/S	1150	550	2.1	NA	NA
USA/ <sup>67</sup>	9	8.2/silt clay loam	0–20	W/S	560	390	1.4	.57	.52
USA/ <sup>69</sup>	9.5	8.2/silt clay loam	0–5	Sorg	651	354	1.8	.65	.54
Canada/ <sup>31</sup>	10	Fine-textured	0–15	W/A/C	1180	840	1.4	3.61	2.72
USA/ <sup>79</sup>	10	5.2/silt loam	0–15	W/B/P	630	380	1.7	3.0	2.3
Australia/ <sup>153</sup>	12	7.8/clay	0–15	W/B	703	697	1.0	.93	.98
Argentina/ <sup>5</sup>	12	5.8/clay	0–5	M/W/S	450	210	2.1	1.55	1.10
USA/ <sup>139</sup>	12		0–20	Sorghum	950	820	1.2	.82	.85
Brazil/(D.S. Andrade, unpublished)	14	4.8–5.0/clay	0–5	W/S/M/C	263	200	1.3	1.25	1.19
Brazil/ <sup>108</sup>	14	clay	0–5	O	371	147	2.5	1.29	.63
USA/ <sup>136</sup>	16	8.4	0–5	M/C	690	400	1.7	.65	.52
Brazil/ <sup>15</sup>	16	4.6/clay	0–15	W/S	255	113	2.3	1.58	.81
Brazil/ <sup>15</sup>	18	4.6/clay	0–15	W/M	595	179	3.3	3.65	1.22

Abbreviations: <sup>a/</sup>NT = No-Tillage; CT = Conventional Tillage. <sup>b/</sup> $C_{\text{mic}}$  = carbon microbial;  $C_{\text{org}}$  = C organic; L = lettuce; C = celery; O = oat; W = wheat; S = soybean; B = barley; Can = canola; M = maize; V = vetch; leg = legume; NA = not available; P = peas; RC = red clover; SF = summer fallow.

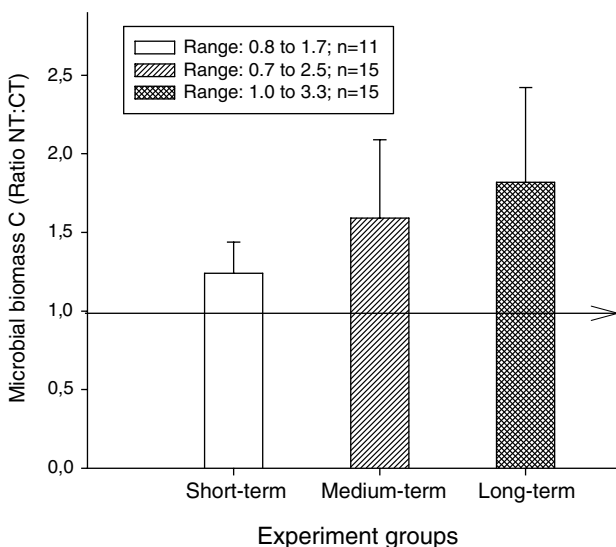
\*Short grass for NT and wheat-fallow cropland for cultivated.





**Figure 3.1** (a) Microbial biomass ( $\mu\text{g C g}^{-1}$  of soil); (b) percentage of C microbial in C organic of soils. Values are an average of data from Table 3.1 of experiment groups according duration: short-term = 0 to 2 years,  $n = 11$ ; medium-term = 3 to 6 years,  $n = 15$  and long-term = 8 to 18 years,  $n = 14$ . Lines on the bars represent standard deviation of experiments means.

experiments (Figure 3.2). As discussed earlier, the results in Figure 3.2 could be explained as due to NT retaining more crop residues and, hence, sufficient substrate to sustain microbial community in higher levels. There is not doubt that the NT cultivation induced a means of survival for soil microorganisms better than CT systems.



**Figure 3.2** Average ratio of microbial biomass C between no-tillage (NT) and conventional tillage (CT) for three groups of experiments. Data calculated from Table 3.1. Lines on the bars represent standard deviation.

Carbon can be found in soil in both labile and resistant forms or forms recalcitrant to attack by microorganisms.<sup>5</sup> Soil microbial biomass is part of the C organic labile fraction and represents only a small portion (1 to 3–8%) of the total soil carbon.<sup>135,148</sup> However, this relatively low fraction has great importance for growing plants as a reservoir of nutrients.<sup>138</sup> The nutrients immobilized in the microbial biomass are more labile than the nutrients contained in the total organic matter. Assessments of microbial biomass and activity can reveal changes in soil organic matter content before these changes can be detected in the total soil organic matter.<sup>96,126</sup> Although it is difficult to establish relationships between microbial parameters and productivity of crops, C microbial biomass can act as an indicator of the overall biological activity of the soil.

Microbial carbon as one of soil labile characteristics varies remarkably throughout the growing season, depending on changes of soil moisture and temperature<sup>30</sup> and other biotic factors. Increases in C microbial biomass were primarily due to adoption of the NT practices (Table 3.1). Microbial activity, as measured by CO<sub>2</sub> production, was larger in NT, with values of basal respiration 70% greater than observed under CT.<sup>15</sup> As there is no inversion of the soil layers in NT systems, this farming practice creates better conditions for microbial growth and activity.

The wider variation observed in microbial biomass increase (Table 3.1) reflects differences in the accessibility of the substratum of C to microorganisms, changes in metabolic patterns, or even different compositions of the microbial community.<sup>5</sup> Doran<sup>51</sup> and Carter<sup>33</sup> reported larger microbial biomass N in agricultural soils under NT, and McCarty et al.<sup>114</sup> showed correlations between N in the biomass and the content of active N in the soil. The increases in microbial biomass and its activity

in the soil have important practical implications for agriculture. Higher soil microbial biomass implies greater temporary immobilization of C, N, and other nutrients and, consequently, smaller losses of nutrients from the soil–plant system. However, higher microbial activity means more C respiration and, consequently, could cause a loss of carbon from the soil–plant system into the atmosphere. For example, tillage may expose substrates and lead to a burst in microbial activity and growth. However, it has been hypothesized that only soils that are rich in clay and with a high surface area have high initial amounts of organic matter that are protected from microbial attack and thus show the highest responses of organic C mineralization after a disturbance. In agreement with this theory are results from clay soils showing that the metabolic quotient in clay soils after plowing and disking had a significant increase in relation to these soils under no-tillage.<sup>15</sup> The metabolic quotient relates to changes in microbial biomass and means that C is released from the soil system. Short-term losses of C as CO<sub>2</sub> have demonstrated that tillage and disturbance of soil contributes to atmospheric CO<sub>2</sub> and accelerates the loss of C from soil.<sup>27</sup> According to the concept of metabolic quotient in soils under NT, this index seems to be closer that observed to situation of less disturbance, for instance, a pasture or forest. Therefore, it is of fundamental importance to predict effects of soil and crop management on microbial populations and their activities.

As has already been illustrated, certain plant species strongly stimulate the microbial development in the rhizosphere. Accordingly, it is possible to select more efficient microbial populations to maintain C, N, and other nutrients in the soil–plant system. This characteristic of the microbial community can be very important in the maintenance of C in soils.<sup>94</sup> Soil microbial biomass was higher for the NT system regardless of the study site, the crop species, and the C levels compared with the CT (Table 3.1). These observations provided additional evidence for the positive effects of NT on the quality of agricultural soils that should promote long-term sustainability, as pointed out by several researchers.<sup>13,15,43,86,111,136,139,143</sup>

Soil management has also affected the  $C_{\text{microbial}}:C_{\text{organic}}$  ratios (Table 3.1/ Figure 3.1b). The greater average difference of  $C_{\text{microbial}}:C_{\text{organic}}$  in NT compared with plowed soils may be also related to accumulation of organic matter. However, in both NT and CT systems, the proportions of organic matter in the microbial biomass are higher in soils from long-term experiments (Figure 3.1b). The relationship  $C_{\text{mic}}:C_{\text{org}}$  in soils from different edaphic climatic conditions ranged from 0.27 to 7.0%, as revised by Anderson and Domsch.<sup>8</sup> Correlations between soil microbial C ( $C_{\text{mic}}$ ) and soil organic C ( $C_{\text{org}}$ ) have been reported by other researchers.<sup>8</sup> These authors found that soils with regular crop rotations had higher  $C_{\text{mic}}:C_{\text{org}}$  ratios. In another study, Insam<sup>94</sup> did not confirm the relationship between soil organic matter and microbial biomass C. Presumably, the physical, chemical, and biological environment for NT practices, known to differ extremely from these for conventional tillage, may have shaped this outcome.<sup>52</sup>

Data from cultivated soils show a higher proportion of microbial C in the total organic C in NT than in CT systems, with values ranging between 0.2 and 4.4 (Table 3.1). This variation was due to the differences in soil type, soil management, and cover crops, as well as to sampling and methodical bias. The changes in the  $C_{\text{mic}}:C_{\text{org}}$  relationship reflect the pattern of organic matter amendments to these

soils, efficiency of the microbial C conversion, losses of C from the soil, and stabilization of organic C in the mineral fractions of the soil.<sup>34,148</sup> The Cmic:Corg relationship may indicate if the soil organic reservoir is in balance, accumulating or decreasing.<sup>8,94</sup> It has been suggested that values of the relationship of Cmic:Corg expresses a balance point and can range from 2.3 for monocultures to 4.4 for crop rotations.<sup>8</sup> Larger or smaller values may indicate carbon accumulation or carbon losses. The Cmic:Corg relationship may be used as a good indicator for alterations of soil organic matter content as a function of soil management. However, these relationships need a deeper insight, in particular better interpretations based on the climatic site conditions. This may encourage farmers to manipulate soil management with the aim of achieving better crop yields.<sup>35,135</sup>

There are a number of intracellular and extracellular enzymes that are accumulated in soil, often related to organic nutrient (e.g., P, N, S, and C) content. These may be used as indices for microbial activities.<sup>48,52</sup> The effects of cultivation on soil enzymes showed that activity of acid phosphatase,<sup>52</sup> arylsulphatase,  $\beta$ -glucosidase, L-glutaminase, dehydrogenase, alkaline phosphatase, invertase, and urease,<sup>47,119</sup> protease,<sup>125</sup> urease<sup>133</sup> was higher in soils with NT than CT systems. Monreal and Bergstrom<sup>119</sup> reported that reduced tillage systems had higher levels of enzymes than cropped soils with CT, and they suggested that these enzymatic factors could be used to assess the impact of crop production systems on the health state of agricultural land.

### **3.3.2 Microorganisms Involved with Decomposition and N Mineralization**

Decomposition of crop residues and soil organic matter is the main process by which nitrogen and other nutrients are made available to plants.<sup>22</sup> Decomposition of crop residues is an essential microbial-mediated process of breakdown of organic matter, which results in production of C and nutrients (e.g., N, P, K and micronutrients) in soil nutritional webs.<sup>104</sup> The N contained in cover crops is a potential source of N for subsequent cropping.<sup>28,163</sup> Temperature, moisture, composition of the decomposer community, and residue quality, including carbon and nitrogen concentrations, are factors that influence plant residue decomposition.<sup>122</sup> It is likely that both edaphic conditions and residue composition affect the diversity as well as activity of a decomposer community.<sup>122,138,163</sup> These microorganisms in turn mediate the processes of nutrient mineralization through decomposition.<sup>52,113</sup>

In the decomposition of soil organic matter, a wide range of compounds of various characteristics and qualities are contained in the original material and are produced during the decay process.<sup>22</sup> Soil incorporation of legume residues initially results in faster and more complete decomposition and release of N.<sup>157</sup> Gupta and Germida<sup>80</sup> suggested that excessive cultivation might cause variations in nutrient mineralization, revealing reduction in the macroaggregates. The mineralized nitrogen reflects the difference in the degree of crop residue incorporation.<sup>128</sup> The NT system had the highest nitrogen mineralization potentials in the top 5 cm and the moldboard treatment the lowest; however, the reverse was true at 10–15 cm.<sup>43</sup> Studies in soils under NT systems indicated that initial N concentration is the major predictor of annual decay rate.<sup>122</sup> The amount of crop that remains and mainly the ratio

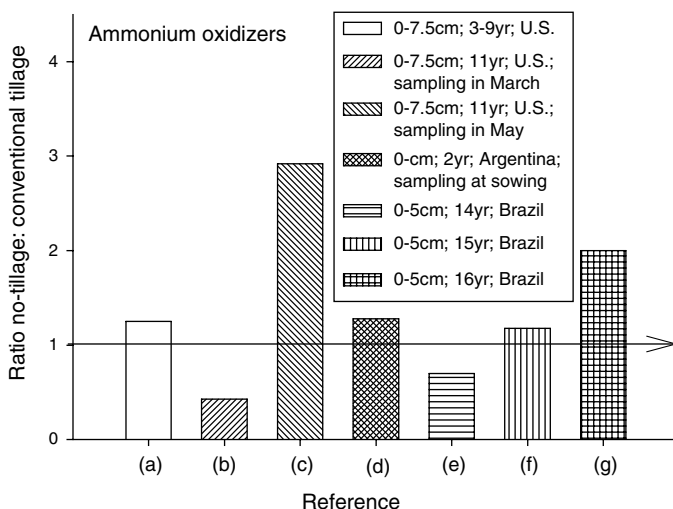
C/N and other qualities inherent in crop residues act on the microorganisms involved in the decomposition processes. Greater quantities of net N mineralization were observed in legume cover crops than in nonlegume crops, for instance, with the release of nutrients.<sup>10</sup> The net rates of mineralization of N in legume straw varied from 54 to 83 kg N ha<sup>-1</sup> in 130 d, while the mineralization N in the wheat straw varied from 7 to 13 kg N ha<sup>-1</sup>. Incorporation of vetch residues, compared with surface placement, results in greater release of soil inorganic N throughout the plow depth.<sup>10</sup> In the NT system, the permanence of crop residues in the surface turns the decomposition and rate of slower mineralization in comparison to cultivated soils.

Decomposing legume residues with a close C:N ratio are also expected to stimulate soil mineralization, which appears to be a temporary limiting step in NT systems. Results obtained under NT systems showed the importance of soil microbial communities in mediating the release of N from crop residues. It was reported on increment in the cellulolytic population and faster decomposition of legume straw with a larger initial concentration of carbohydrates, and of N than with wheat.<sup>10</sup> Thus, it has been proposed that this system with surface-maintained crop residues might provide a continuous resource in space for many decomposer organisms.<sup>86</sup> By using an index, which is a ratio of the sum of crop weeds, insects, and litter to the sum of inputs such as rainfall and fertilizer, House et al.<sup>86</sup> indicated that N is recycled slowly under NT cropping practice.

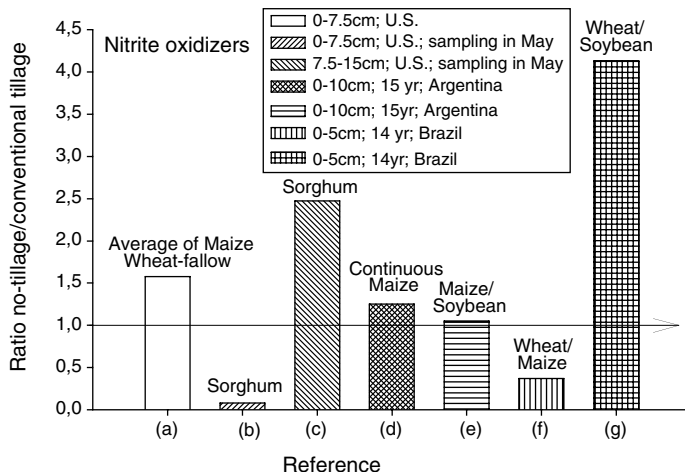
In most arable soils, fungi often account for a large part of the microbial protoplasm<sup>2,19,122</sup> due to the large diameter and extensive network of their filaments. Though enumeration procedures used with microorganisms suggest that fungi are a small component of soil microbial communities, they do in fact make up a significant part of the biomass.<sup>2</sup> This group of microorganisms is assumed to be more susceptible than bacteria to disturbance caused by plowing.<sup>159</sup> Other studies have also reported that fungi tend to be the dominant microorganisms where plant residues are left on the soil surface or in the litter layer of the forest floor. Fungal abundance in the surface 0–5 cm of soils was significantly higher in NT than in CT systems across six long-term field experiments.<sup>70</sup> On the other hand, as expected due to the plate count method used, the population size of phosphate-solubilizing microorganisms, mainly fungi, increased after plowing in conventional tillage systems.<sup>43</sup>

Increases in the activity of associated bacteria—nitrogen fixers (*Azospirillum* spp.), ammonifiers, nitrifiers, and microorganisms that solubilize phosphate in NT, in relation to CT were observed.<sup>43</sup> Although these differences were not large, there was less variability under the NT system. In soils under CT, higher variations and microbial densities were also observed with enhanced microbial activities after crop harvest. The findings show that NT is less stressful to microbial populations, providing a balance between soil biota and the physicochemical components, resembling more soil conditions similar to those of a native forest.

Nitrification is an important biological process mediated by microorganisms; it transforms ammonium to nitrate ions strongly exposed to losses through leaching or denitrification.<sup>20</sup> A general comparison of ammonium and nitrite oxidizer microorganisms between NT and CT systems using average counts across locations is given in [Figures 3.3](#) and [3.4](#). The NT:CT ratio of most probable numbers (MPN) of both



**Figure 3.3** Effects of soil cultivation (no-tillage = NT and conventional tillage = CT) on populations of ammonium oxidizers. Values are ratio of  $\log_{10}$  MPN of cells  $g\ soil^{-1}$  in NT:CT. Adapted from (a)<sup>52</sup>, average of 7 locations, maize and wheat-fallow; (b)<sup>150</sup>, sorghum, soil sampling in March; (c)<sup>150</sup>, sorghum and soil, sampling in May; (d)<sup>50</sup>, wheat (e); (f) and (g) D.S. Andrade, unpublished, rotation wheat/soybean.



**Figure 3.4** Effects of soil cultivation (no-tillage = NT and conventional tillage = CT) on populations of nitrite oxidizers. Values are ratio of  $\log_{10}$  MPN of cells  $g\ soil^{-1}$  in NT:CT. Adapted from (a)<sup>52</sup>, W/maize = maize and wheat-fallow, 3–9 years; (b)<sup>150</sup>, 11 years, sorghum, 0–7.5cm; (c)<sup>150</sup>, 11 years, sorghum, 7.5–15cm; (d)<sup>125</sup>, 15 years, maize/maize; (e)<sup>125</sup>, 15 years, maize/soybean; (f) D. S. Andrade, unpublished, W/M = wheat/maize and W/S = wheat/soybean, D. S. Andrade, unpublished, W/S = wheat/soybean.

ammonium and nitrite oxidizer microorganisms in general had higher values with respect to CT in some experiments. Doran<sup>52</sup> related lower N-NO<sub>3</sub> levels in NT, with lower nitrifying and greater denitrifying potential as compared with CT, but this trend is highly variable depending on location in the soil profile, sampling times, and crop rotations (Figures 3.3 and 3.4). Measurements of the activity of specific soil microorganisms can indicate changes that may be occurring due to soil cultivation. In general, the largest contribution of carbon, soil water, and temperature favored higher microbial activity of different microorganisms.

### 3.3.3 Rhizobia/Bradyrhizobia Population

The contribution of the symbioses between rhizobia and legumes in recycling nutrients to exploit in crop rotations is widely documented. This symbiotic association plays a key role in soils under NT and cropping rotation systems. Tuned crop sequences provide a potential tool to improve nitrogen supply for both legumes and nonleguminous crops in agroecosystems.<sup>73</sup> One of the major benefits expected from legume growing is that it will add N to the soil through N<sub>2</sub> fixation. The introduction of legume cover crops seems to guarantee the maintenance of soil N reserve.<sup>7</sup> Crop sequencing and tillage practices influence the soil mineral N status of soils.<sup>56</sup>

Studies at several locations in Australia showed that lupine, pea, faba bean, chickpea, and medic may provide more than 50% of crop N requirements through N<sub>2</sub> fixation.<sup>64</sup> Despite this and other subsequent studies on rhizobia-legume symbioses, there is little information available on rhizobial population diversity in soils under NT. The kind of tillage and crop rotation systems may quantitatively and qualitatively affect rhizobial populations in soil.

Legume residues represent a valuable source of N for crops, particularly when the amounts fixed during growth are greater than the quantities of N harvested in the seed.<sup>87</sup> In this section, the main analysis is based on nodulation and N<sub>2</sub> fixation of soybean and common bean (Table 3.2). Both legumes are crops that provide cash income from grain but require no N fertilizers due to their ability to fix atmospheric N. Soybean and common bean, when included in crop rotation, can improve the N nutrition, e.g., of subsequent cereals. Common beans have been regarded as a poor N<sub>2</sub> fixer.<sup>78</sup> However, some field studies showed significant contributions from N<sub>2</sub> fixation.<sup>59,129,142</sup> In Brazil, soybean produced well-nodulated plants with seed yields of approximately 2500 kg ha<sup>-1</sup> without any N fertilizer.<sup>93</sup> These crops fit into rotations of soybean or bean–fallow–maize; soybean or common bean/winter cereal (wheat, oats)–fallow–maize; or soybean or common bean winter cereal–soybean rotations. The effects of tillage on N<sub>2</sub> fixation and rhizobial populations nodulating pea (*Pisum sativum* L) have also been studied (Table 3.2).

Improving the soil environment to match the living requirements of N<sub>2</sub> fixers seems to be the key component responsible for the significant increase in the number of bacterial cells and nodules under NT (Table 3.2). Increases in soybean nodulation were observed independent of that rotation. Soybean seeds inoculated with commercial peat-based culture of *Bradyrhizobium japonicum* CB1809 produced more nodules in no-tilled soil and had a greater nodule mass per plant than soybeans grown on cultivated soils.<sup>87</sup> The authors suggested that major effects of tillage could

**Table 3.2 Effects of Cultivation on Most Probable Numbers (MPN) of Rhizobia, Legume Nodulation (Mass and Number of Nodules) and N<sub>2</sub> Fixed**

Specie/ References	Yr	Crop Rotation/ Treatment	Rhizobia			Nodule			N fixed			
			NT	CT	Incr.	NT	CT	Incr	NT	CT	NT	CT
			Log <sub>10</sub> (MPN)			—mg pl <sup>-1</sup> —			—%—			
			(%)			—%—			—Kg ha <sup>-1</sup> —			
Soybean/ <sup>158</sup>		L/M/T	—	—	—	194	113	72	—	—	—	—
		S/W	—	—	—	120	80	50	—	—	—	—
	7	S/W/M	—	—	—	150	70	114	—	—	—	—
		S/W/C	—	—	—	154	62	148	—	—	—	—
		S/W	3.66	3.20	14	98	62	58	—	—	—	—
Soybean/(D.S. Andrade unpublished)	14	S/W/M	3.77	3.17	19	130	87	49	—	—	—	—
		S/W/C	3.30	3.08	7	127	49	159	—	—	—	—
		S/W/C/M	3.43	3.28	5	<sup>2/</sup> —	—	—	—	—	—	—
	17	<sup>1/</sup>	4.86	4.07	8	—	—	—	—	—	—	—
Soybean/ <sup>68</sup>	6	S/W/M/P	6.06	5.36	13	—	56	178	—	—	—	—
Soybean/ <sup>9</sup>	2	Past/S	—	—	—	—	113	58	298	208	110	55
Soybean/ <sup>67</sup>	17	S/W	3.70	3.20	16	—	—	—	—	—	—	—
Chickpea/ <sup>66</sup>	1	Sorghum	—	—	—	—	—	—	90	85	103	97
Bean/ <sup>109</sup>	—	CIAT899	—	—	—	<sup>3/</sup> 67	57	17	—	—	—	—
Bean/ <sup>12</sup>	3	Nfertilizer	—	—	—	24	12	100	—	—	—	—
		No-Inoc	—	—	—	65	21	209	—	—	—	—
		CIAT899	—	—	—	49	18	172	—	—	—	—
Bean/ <sup>92</sup>	3	—	4.59	3.40	35	113	80	41	—	—	—	—
Pea/(D.S. Andrade unpublished)	6	S/W/M	2.19	2.05	7	—	—	—	—	—	—	—
Pea/ <sup>63</sup>	—	Wheat	—	—	—	—	—	—	—	—	72	63

Abbreviations: NT = no-tillage or CT = conventional tillage; Incr = increment; L = lupinus; M = maize; T = triticale; S = soybean; W = wheat; C = cotton; P = pea; Past = pasture; No-Inoc = not inoculated; (—) = not available. <sup>1/</sup>Values are average of rotations wheat/soybean; wheat/soybean/maize and wheat/maize; <sup>2/</sup>no soybean this year; <sup>3/</sup>values are average of WBR22–34 and WBR22–55 cultivars.

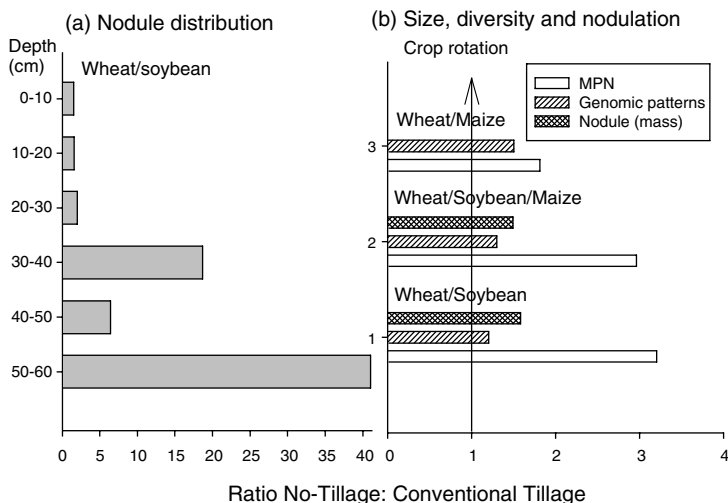


be due to changes in concentrations of soil nitrate. They implied that there is considerable evidence in the literature that cultivation stimulates mineralization of organic matter in soils, resulting in higher concentrations of nitrate in cultivated soils compared with uncultivated (NT) soils.<sup>52</sup> However, twice the amount of nitrate in a clay soil under NT in relation to CT after 16 years of cultivation was observed (D. S. Andrade and A. Colozzi-Filho, unpublished). Some studies on soybeans<sup>87</sup> and common bean<sup>93</sup> did not support the reported previous observations, with inferior yields in the NT systems. Especially in the first year after pasture, the potential for increased N<sub>2</sub> fixation in soils under NT may represent a more significant benefit.<sup>87</sup>

Supplies of nutrients such as N can be altered under adverse soil conditions, such as intensive cultivation. Two soil physical conditions—temperature and moisture content—are critical to the growth of rhizobia and to nodulation and N<sub>2</sub>-fixation processes. Soils under the NT system develop extremely favorable conditions for symbioses, such as decreases in the temperature of the soil of up to 10°C<sup>107</sup> and greater availability of water, resulting from the increment in the aggregate stability and increases in the numbers of macropores. The greater quantities of plant residues, covering the no-tilled soils at sowing, protected the inoculating rhizobia from extremes of temperature and moisture fluctuations, resulting in increased survival of the microorganisms, better rhizosphere colonization, and increased nodulation.<sup>56,92,158</sup> The presence of fenolic compounds and the induction of  $\beta$ -galactosidase activity, nodulation gene fusions, showed increased nodulation activity in NT soils.<sup>89</sup> The larger number of cells of *Bradyrhizobium/Rhizobium* and the higher accumulation of inducers of *nod* genes in soils under NT seem to be due to edaphic and climatic conditions that are more favorable for nodulation, with increments ranging from 17 to 209%, as shown in several studies (Table 3.2). The results also showed a better distribution of soybean nodules within the soil profile in this system (Figure 3.5a).

Proper soil and crop management is fundamental to keeping biodiversity and optimizing the benefits that will result from microbiological processes.<sup>92</sup> Tillage and cropping history can also influence occurrence and diversity of bacterial N fixers in the soil. When disturbances in the soil–plant system occur, the diversity of microorganisms seems to be the first to respond. A higher diversity of rhizobial isolates was confirmed for NT soils compared with other tillage treatments.<sup>66</sup> Rhizobial isolates nodulating soybean from soils managed under the NT system were grouped in clusters different from those of inoculated plants maintained under CT management.<sup>91</sup> Coutinho et al.<sup>44</sup> reported that diversity of rhizobial populations was significantly reduced in soil cultivated with soybean in comparison to original uncultivated pasture.

The different organic exudates released by crop can influence the composition of the microbial population. The cultivation of host species has clearly improved the size of indigenous *Phaseolus*-nodulating rhizobia populations.<sup>11,103</sup> Regarding qualitative differences, higher diversity of *Phaseolus*-nodulating rhizobia was observed in the presence of the host plant in monoculture or intercropping in comparison to monocropping with maize.<sup>89</sup> Figure 3.5b shows an example of changes in diversity of *Bradyrhizobium* isolates from soil cropped with soybean/wheat rotation. It is



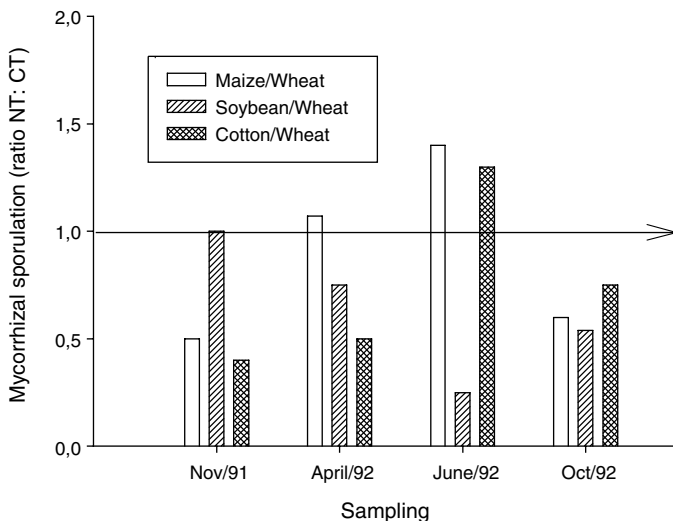
**Figure 3.5** Ratio of no-tillage:conventional-tillage, (A) Nodule distribution in the soil profile; data adapted from [158], (B) Most Probable Number (MPN) and diversity measured by genotypic patterns of *Bradyrhizobium japonicum*, data from Reference 66 and soybean nodulation (D. S. Andrade, unpublished).

possible to take advantage of soil diversity and soil adaptation to certain more efficient and competitive strains.<sup>66,91</sup>

### 3.3.4 Mycorrhizal Fungi

Arbuscular mycorrhizal (AM) are soil-inhabiting fungi that maintain symbiotic relationships with the majority of crop plant species, contributing to mineral nutrition, especially of phosphorus, for the host plant.<sup>105</sup> Several studies have shown that tillage is the most direct and drastic stress factor in the formation of mycorrhizas, reducing the infective potential of the soil.<sup>54,61,95</sup> When the vegetation is removed, a break in the flow of exudates from roots and photosynthetic products occur, affecting the populations of AM fungi. The fungal hyphae form an extensive network in agricultural soils that becomes functional after contact with seedlings.<sup>117</sup> When the soil is disturbed, this hyphae network is fragmented by the mechanical tillage effects, and the cellular contents can be lost. This reveals loss in vitality as propagules, reducing the inoculum potential of the tilled soil.

Spores are the resistant stage in the life cycle of many fungi, including AM fungi populations. Assessing spore densities in soil is considered as an indirect measurement<sup>97</sup> and an adequate method for studying effects of cultivation on AM fungal communities. Higher mycorrhizal sporulation has been found in soil under CT than in NT soils,<sup>42,43</sup> which is probably due to the distribution of hyphae in response to the traditional practices of plowing that induces stress conditions. The authors also suggested that higher stability of the mycorrhizal system in soils under NT contributed to a more balanced relationship in the microbial community. The lack of soil

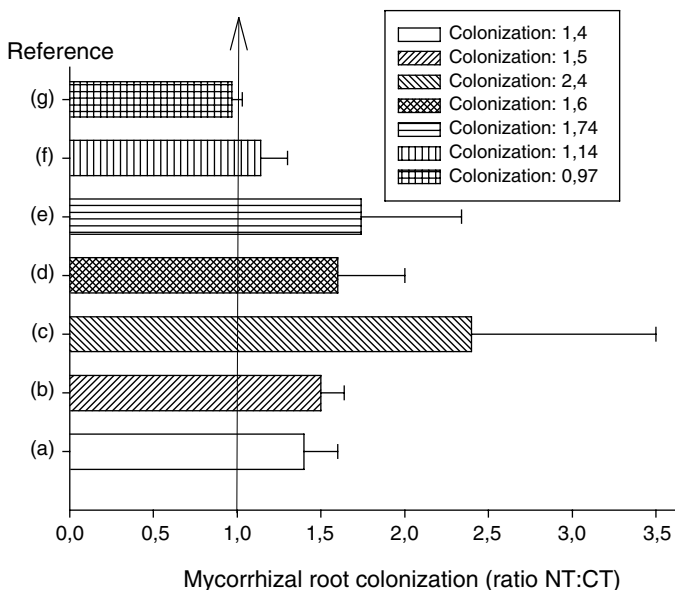


**Figure 3.6** Spore populations of arbuscular mycorrhizal fungi sporulation measured as ratio of no-tillage (NT): conventional tillage (CT). The soil had previously been cropped for 15 years with wheat in the winter and maize, soybean and cotton in the summer (A. Colozzi-Filho, unpublished).

disturbance makes possible a more permanent network of external hyphae and colonized roots; consequently, it guarantees that there will be an inoculum for subsequent crops to maintain the potential infectivity of the soil.

Data from a long-term study showed effects of tillage on AM fungi sporulation (Figure 3.6). The number of spores was higher in soil under CT, except for maize/wheat and cotton/wheat rotations in the winter sampling (A. Colozzi-Filho, unpublished). On the other hand, Kurle and Pflieger<sup>105</sup> reported larger AM fungi sporulation in soils under low-input management. As there are different components involved, such as host plant, AM fungi species, and soil and climatic conditions, it becomes difficult to make a comparison of the several field evaluations. It is possible that the most sporulation, observed in the tilled soils, is linked to the stability of the agroecosystems. According to Siqueira,<sup>144</sup> agricultural systems under intense management can select AM fungi, and this selection does not always address symbiotic efficiency but rather survival, which, in stress situations, seems to be linked to the propagation of resistant structures. It is likely that soil tillage (plowing) is a factor selecting species of mycorrhizal better adapted to stress conditions, and the largest soil sporulation is an alternative means for fungi to survive in the soil system.

Tillage had provoked the predicted effects on mycorrhizae in various field experiments. Greater mycorrhizal root colonization was confirmed for NT wheat or maize compared with the same crops grown in tilled soil treatments.<sup>43,71</sup> Under NT soil environments crop rotation and adjusted nutrient management have obviously directly enhanced the AM fungi sporulation and the hyphae network and indirectly through crop species, colonization intensity, and fungal diversity.<sup>55</sup> Results from



**Figure 3.7** Effects of tillage systems on root mycorrhizal colonization measured as ratio of no-tillage (NT): conventional tillage (CT). Adapted from: (a) A. Colozzi-Filho, unpublished; (b);<sup>100</sup> (c);<sup>121</sup> (d);<sup>71</sup> low input; (e);<sup>116</sup> maize; (f);<sup>116</sup> soybean; (g).<sup>72</sup>

different crop management showed that NT increased mycorrhizal root colonization (Figure 3.7). AM fungi propagules, such as spores and mycorrhizal roots, are associated with a network of hyphae. The greatest colonization that was observed in NT cultivated with wheat (Figure 3.7) strongly supports this hypothesis. The reduction observed in root colonization under tilled soil conditions reflects changes in the potential of soil natural infectivity.

In addition to hyphae, soil inversion by plowing exposes present propagules (spores, hyphas, and colonized root fragments) at the soil surface to temperature extremes and predators. The adverse tillage effects on the total AM fungi mycelium in the spring is reported to suppress the micorrhizal activity in subsequent cropping,<sup>100</sup> revealing declines in nutrient uptake and crop yields.<sup>61</sup> The authors reported that there was a significant correlation between colonization and the development of the corn crop, with the highest levels in NT systems. Likewise, in soils cultivated with the successions wheat/soybean, wheat/maize, and wheat/cotton, wheat root colonization was higher in NT than CT systems.<sup>41,43</sup> The mycelia reduction in root colonization caused by tillage may explain the negative relationships that are observed between liming and P absorption in some studies.<sup>62,65,116</sup>

Besides acting on sporulation, tillage has a selective pressure on soil AM fungi communities. In areas cultivated with maize/soybean/wheat rotation, more spores of *G. occultum* were found in soils under NT, but more *G. etunicatum* and other species of *Glomus* sp. in soils under CT.<sup>54</sup> Soil tillage favors the proliferation of specific species, although these may not be the best to increase phosphorus absorption and crop productivity. Most of the evidence is that soil tillage has negative

effects on the soil potential inoculum compared to NT systems. Increases are usually observed in the P content of soils after some years following transition to NT management. Colonization of plant roots, production of spores, and responses of plants in terms of growth and production can be affected by an abundance of P in the soil.<sup>1</sup> The benefits of mycorrhizas to plants depend not only on the amount of P in the soil but also the degree of mycorrhizal dependence of the plant. This could explain research results that showed only small decreases in the colonization of plants with additional high doses of P to the soil.<sup>115</sup>

The AM fungi effectiveness and the efficiency of their association with plants can vary in the function of both the host plant and the symbiotic species.<sup>85,120</sup> This variability suggests the possibility of cultivating plants that multiply fungi efficiently and thus increase the natural inoculum potential of soil and the efficiency of the symbiosis.<sup>147</sup> Otherwise, the use of nonmycorrhizal species in rotations can reduce soil infectivity<sup>21,82</sup> and, consequently, exert adverse effects on the establishment of mycorrhizas on the following crop. Likewise, long periods of fallow can also drastically reduce the natural infectivity of soil.<sup>152</sup> NT systems improved AM fungi root colonization of several crops rotations (Figure 3.7). Therefore, the strategy of rotation choice should address the management of populations of native AM fungi, always considering the possibility of increasing or, at least, maintaining their diversity in the agroecosystems.

Positive effects of crop rotations, expressed as enhanced root colonization or production of mycorrhizal spores, have been related to several crop sequences. For instance, Sieverding<sup>141</sup> observed higher colonization in cassava (*Manihot esculenta*) when cultivated in rotation with peanut (*Arachis hypogaeae*) than in monoculture. Baltruschat and Dehne<sup>16</sup> showed that the AM fungi potential inoculum in soils after 4 years of rotations was considerably increased compared with soil under maize monocropping. Colozzi-Filho and Balota<sup>42</sup> reported positive effects on the number of mycorrhizal spores in the soil of cropping maize in succession or rotation. After 3 years of cultivation, spore densities in the soil were larger when maize followed wheat or soybean as a synergistic effect in the first 2 years. The largest numbers of spores in soil were observed in corn monocrops.<sup>77</sup> The beneficial effect of graminaceous plants on the sporulation of some AM fungi has been related to their aggressive root systems (Figure 3.6). There is evidence that the incentives provided by the exudates appear to be unrelated to the availability of nutrients that can act as molecular signs, stimulants of spores germination, growth mycelium hyphae, and the rate of root colonization.<sup>145</sup>

Rotations of different crop species can be important in the maintenance of soil biological balance, aiming at avoiding selection of microbial species promoted by monocropping. The changes in efficiency and composition of AM fungi native population due to continuous cultivation can be related to declines in the productivity of monocropping, as suggested by Schenck and Siqueira.<sup>137</sup> The monocropping, besides modifying populations of native AM fungi, could result in selection of ineffective species, reducing the efficiency of the native population.<sup>97</sup> This effect can be minimized by crop rotations.

Several studies have shown that crop rotations act positively not only on the mycorrhizal activity, through the increase in the natural potential inocula of soils,

but also on the diversity of AM fungi species;<sup>77,98,155</sup> thus, cropping can modify the composition of soil native population. Occurrence of preferential AM fungi–plant associations has been observed. Studying soybean and maize cultivated in monocropping or rotations, Gomes-da-Costa<sup>77</sup> observed quantitative and qualitative changes in AM fungi communities related to host plants. It was observed that *A. mellea* multiplied more quickly under soybean crops, and conditions for most rapid multiplication rates were most favorable under maize. *Scutellospora coralloides*, *S. calospora*, and *S. heterogama* were found in the rhizosphere of corn cultivated in monocropping, being undetectable in soils when soybean was grown in rotations. *Gigaspora ramisporophora* showed preference for continuous soybeans. On the other hand, *Acaulospora longula* had no host specificity and was not affected by crop rotations.

The maximum efficiency in plant mycorrhizal associations can be obtained through soil and crop management including soil NT systems as an alternative to increase root colonization and crop rotations with plants that create a selection pressure on AM fungi favoring the multiplication of efficient species.

### 3.4 HOW TO MAINTAIN SOIL BIODIVERSITY IN AGROECOSYSTEMS

In NT ecosystems, the use of crop rotation is recommended because the cultivation of different species alters the amounts and quality of plant residues incorporated into the soil, thereby increasing cover and stimulating microbial biodiversity.<sup>112,131</sup> The benefits of rotations for crop production are recognized, have been studied widely, and are reviewed by Kumar and Goh.<sup>104</sup> However, the exact reasons for crop production increases have not been established. Variable responses of crops to fertilization indicate that the factors and mechanisms involved have yet to be discovered. Soil microorganisms, including rhizobia, mycorrhizal fungi, and other beneficial microorganisms, may be one of these factors and may play a role in the effects of crop rotations and the gains in yields. As suggested by Doran and Parkin,<sup>53</sup> the measurement of microbial activity of specific microorganisms can be indicative of soil quality and of the relationships between these measurements and other biotic and abiotic factors of the soil.

The soil microbial communities significant impact several key processes related to soil aggregation, the availability and recycling of nutrients, decomposition of organic residues, biological fixation of nitrogen, and the absorption of nutrients through the action of mycorrhizas. The practice of NT and crop rotations can alter several soil properties, and generally these effects have been regarded as positive for the microbial community, its activity, and some populations of microorganisms such as cellulolytic microorganisms, phosphate solubilizers, rhizobia, ammonifiers, and mycorrhizal fungi. Both soil and crop management acting on these processes influence the productivity and sustainability of an agroecosystem. Intensification of soil exploitation may result in loss of soil microbial biodiversity.<sup>74</sup> For instance, some agricultural practices, such as monocropping, select microbial populations, thereby reducing their diversity and contributing to the degradation of agroecosystems. Alternative management practices that increase microbial diversity and activity

should be adopted; this would maximize the contribution of microorganisms. Such practices should also highlight the importance of biological activity in conservation agriculture in the tropics with a need to define strategies that can support crop production.

In conclusion, as sustainable agriculture seeks to produce optimal yields with good economic returns and at the same time maintain soil quality, the challenge will be how to sustain this biological equilibrium.

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